

Neutron β Decay

Status and Future of the Asymmetry Measurement

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With more intense sources of cold and ultracold neutrons becoming available and with improved experimental techniques being developed, determination of $|V_{ud}|$ from neutron β decay with a similar precision to that from superallowed β decays is within reach. Determination of $|V_{ud}|$ from neutron β decay, free from nuclear corrections, hold the most promise for a further improvement of the determination of $|V_{ud}|$. The current and future neutron β decay correlation experiments including the UCNA experiment at Los Alamos National Laboratory are reviewed.

INTRODUCTION

High precision electroweak measurements provide stringent tests of the standard model (SM) and search for what may lie beyond it. A deviation from expectations based on our knowledge of the SM would be indirect evidence for new physics. These high precision tests complement direct searches for new physics using high energy colliders.

Unitarity of the Cabibbo-Kobayashi-Maskawa matrix (CKM matrix) requires that the first row satisfy

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1. \quad (1)$$

A deviation from unity could arise from additional heavy quark mixing. Also, because the extraction of these CKM matrix elements involves comparison between muon decay and semileptonic decay of hadrons, any new physics that causes a violation of quark-lepton universality would cause a deviation from unity.

The value of $|V_{ud}|$ has been obtained from superallowed nuclear β decays, neutron β decay, and pion β decay. The current determination of the value of $|V_{ud}|$ is dominated by superallowed nuclear β decays [1]. The value is (using an updated electroweak radiative correction [2]) $|V_{ud}| = 0.97377(11)(15)(19)$. The uncertainties are (1) nuclear structure uncertainty added in quadrature with the experimental uncertainty in the ft value, (2) uncertainty in coulomb distortion effects, and (3) uncertainty from quantum loop effects. Although the third uncertainty is common to both $|V_{ud}|$ determination from nuclear β decay and that from neutron β decay, $|V_{ud}|$ determination from neutron β decay is free from nuclear corrections that are associated with uncertainties (1) and (2). Therefore, neutron β decay can in principle provide a determination of $|V_{ud}|$ with a smaller theoretical uncertainty than nuclear β decay.

With more intense sources of cold and ultracold neutrons becoming available and with improved experimental techniques being developed, determination of $|V_{ud}|$ from neutron β decay with a similar precision to that from nuclear β decay is within reach. This will provide a useful cross check of the current determination of $|V_{ud}|$

from nuclear β decays, in particular of the nuclear dependent corrections. Furthermore, precision measurements of neutron decay parameters hold the most promise for a further improvement of the determination of $|V_{ud}|$.

Determination of $|V_{ud}|$ from neutron β decay requires knowledge of the neutron lifetime τ_n and the ratio of the axial to vector coupling constants $\lambda = G_A/G_V$. In the following, after a brief review of the current status of the $|V_{ud}|$ determination, we will review the current and future neutron β decay correlation measurements, which provide determination of λ . The status of the neutron lifetime experiments is reviewed in Ref. [3].

STATUS OF V_{ud} DETERMINATION FROM NEUTRON β DECAY

The value of $|V_{ud}|$ is determined by comparing the vector coupling constant of β decay, G_V , to the Fermi coupling constant, G_F , determined from muon decay. In the case of free neutron β decay, knowledge of both neutron lifetime τ_n and the ratio of the axial to vector coupling constant $\lambda = G_A/G_V$ is required to determine G_V .

$$\begin{aligned} |V_{ud}|^2 &= \frac{G_V^2}{G_F^2(1 + \Delta_R)} \\ &= \frac{2\pi^2}{G_F^2 m_e^5 \tau_n (1 + 3\lambda^2) f^R (1 + \Delta_R)}, \end{aligned} \quad (2)$$

where Δ_R is the quantum loop correction mentioned earlier, m_e is the electron mass, f^R is the phase space factor (including the outer radiative correction). Numerically [2],

$$|V_{ud}|^2 = \frac{4908.7(1.9) \text{ s}}{\tau_n(1 + 3\lambda)}, \quad (3)$$

where the uncertainty quoted is from Δ_R .

The value of λ is determined from measurements of decay correlations. The differential decay rate, averaged over electron spin, is given by [4]

$$\begin{aligned} \frac{dW}{dE_e d\Omega_e d\Omega_\nu} &\propto p_e E_e (E_0 - E_e)^2 \\ &\times \left[1 + a \frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + \langle \boldsymbol{\sigma}_n \rangle \cdot \left(A \frac{\mathbf{p}_e}{E_e} + B \frac{\mathbf{p}_\nu}{E_\nu} \right) \right], \end{aligned} \quad (4)$$

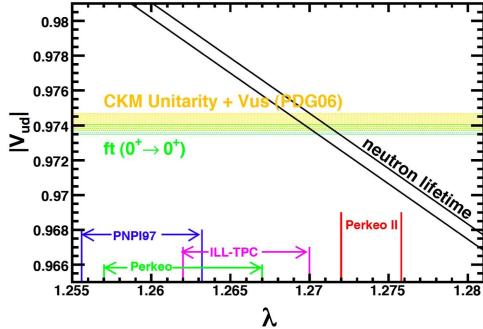


FIG. 1: The current experimental status of the determination of $|V_{ud}|$. The values of λ from the four recent measurements are shown by four brackets along the λ axis as well as the constraints from the world average of the neutron lifetime measurements as given by the Particle Data Group [10]. (Note that the average given by the Particle Data Group [10] does not include the recent measurement reported in Ref. [11].) The combination of a λ measurement and the neutron lifetime measurement determines the value of $|V_{ud}|$. Also shown are the $|V_{ud}|$ determination from nuclear β decay and the $|V_{ud}|$ determination from kaon and B-meson decays and the assumption of CKM unitarity.

where m_e is the electron mass, E_e the electron energy, \mathbf{p}_e the electron momentum, E_ν the neutrino energy, \mathbf{p}_ν the neutrino momentum, and σ_n the neutron spin. Coefficients a , A , and B depend only on λ in the SM. Among them, A is the most sensitive to λ with $\frac{d\lambda}{dA} = 2.6$. a has a similar but slightly reduced sensitivity to λ with $\frac{d\lambda}{da} = 3.3$. B is much less sensitive to λ with $\frac{d\lambda}{dB} = 13.4$. So far, the determination of λ from free neutron decay has been provided by measurements of A . The uncertainty in λ from the most precise measurement of a [5] is more than ten times larger than the uncertainty in λ from the most precise measurement of A [6]. Therefore the main focus of this review on is A measurements.

The current experimental situation is graphically summarized in Fig. 1. The precision with which the recent four measurements [6, 7, 8, 9] determined the value of A ($0.6 - 1.6\%$) is not sufficient to make a determination of $|V_{ud}|$ from neutron β decay with a precision comparable to that from nuclear β decay. Furthermore, the agreement among the four measurements is poor. Clearly a new measurement of A with a higher precision is warranted.

A typical experimental arrangement for A coefficient measurements involves measuring the forward-backward asymmetry of electron emission with respect to the neutron spin in polarized neutron β decay. Polarized neutrons (a beam of cold neutrons in almost all cases) are let decay in a decay volume and electrons from the neutron decay are guided by a strong magnetic field towards one

of the two electron detectors located at the ends of the decay volume. When the detectors have a 4π coverage of β decay events, the asymmetry in the count rate in the two detectors can be related to the A coefficient as follows:

$$A_{\text{exp}}(E_e) = \frac{N_1(E_e) - N_2(E_e)}{N_1(E_e) + N_2(E_e)} = \frac{1}{2}PA\beta, \quad (5)$$

where E_e is the electron's energy, $N_{1(2)}$ is the count rate in detector 1(2), P is the average polarization of the neutrons, and β is the velocity of the electron in the units of the velocity of light.

Three major sources of systematic uncertainties can be identified in the previous experiments. They are (1) neutron polarization determination, (2) background, and (3) detector effects including backscattering of β particles. As evident from Eq. 5, the polarization determination has to be done to a precision better than the precision to which A is to be determined. Also, incomplete knowledge of the background signal will lead to an erroneous determination of $N_{1(2)}$, thereby giving an erroneous determination of A . With regard to the detector effects, due to the small end point energy of the electron spectrum ($E_e^0 = 782$ keV), a significant fraction ($\sim 10\%$ for plastic scintillation counters) of electrons from neutron β decay directed to one detector can backscatter from the surface of the detector and are detected by the other detector. A non-negligible fraction of the backscattered electrons leave undetectably small energy deposition in the first detector, hence introducing an error in the asymmetry determination. (These electrons are called missed backscattered electrons.) Understanding the backscattering of low energy electrons and properly characterizing the detector response is clearly of vital importance.

In order to address the unsatisfactory situation represented in Fig. 1, measurements of A with a precision of $\delta A/A = 0.2\%$ or better are required (The uncertainty reported in Ref. [6] (PerkeoII experiment) is $\delta A/A = 0.6\%$). Clearly, these measurements need to address the above-mentioned systematic issues. In Table I, major systematic corrections applied to the results of the recent four measurements are listed. It is seen that corrections that are significantly larger than the reported uncertainty were applied. Experiments with low background, high polarization ($> 99.9\%$), and small detector effects are highly desirable since they do not require large corrections, thus improving the reliability of systematic error assignment.

ONGOING AND FUTURE NEUTRON β -DECAY CORRELATION EXPERIMENTS

There are in fact several experiments ongoing or planned to measure A with a higher precision.

TABLE I: Major systematic correction in the recent A measurements

Experiment	A	Systematic corrections	
		Polarization	Background
Perkeo (1986)	-0.1146(19)	2.6%	3%
PNPI (1991)	-0.1116(14)	27%	small
ILL-TPC (1995)	-0.1160(15)	1.9%	3%
Perkeo II (2002)	-0.1189(7)	1.1%	0.5% ^a

^aAfter environmental background(15%) was subtracted.

Since their last publication [6], Perkeo II collaboration have implemented some upgrades, including a new ballistic supermirror guide for a higher neutron flux [12] and a new crossed supermirror polarizers for a higher neutron polarization [13]. At the same time, a new experiment Perkeo III has been developed.

There are two major efforts under way to measure A in US. The UCNA experiment [14], currently being commissioned at Los Alamos National Laboratory, aims at a 0.2% measurement of A using ultracold neutrons (UCNs).

The abBA collaboration proposes to perform a simultaneous measurements of a , A , B , and the Fierz interference term b (which is zero in the SM) at the Spallation Neutron Source (SNS) [15]. The goal of the abBA experiment is to determine a , A , B , and b with an absolute precision of $\sim 10^{-4}$. In order to address known problems in previous experiments, the abBA experiment includes several new features such as, the use of pulsed neutron source, the use of a polarized helium-3 transmission cell as a neutron polarizer, coincidence detection of the decay electrons and the protons, and the use of segmented silicon detectors. Since in the SM, a , A , and B depends only on λ , the consistency among a , A , and B will provide a powerful check for potential systematics.

There are also efforts to improve the precision of a . The aCORN experiment, being prepared at NIST, aims to determine a to a statistical precision of 1% or less by performing coincidence detection of electrons and recoil protons and selecting two kinematic regions such that a comparison of the rates in the two regions directly yields a measurement of a [16]. The aSPECT experiment, currently being developed at Mainz and will be run at ILL, will measure the recoil proton energy spectrum using a magnetic spectrometer with electrostatic retardation potentials [17]. The expected precision is $\delta a/a = 0.25\%$.

Below, we discuss the UCNA experiment more in detail.

UCNA Experiment

The goal of the UCNA experiment is a 0.2% measurement of A . Unlike previous experiments, which used a

beam of cold neutrons from a reactor, the UCNA experiment uses UCNs produced by a pulsed spallation UCNs source [18]. UCNs are neutrons with total kinetic energy less than the effective potential U_F presented by a material boundary. These neutrons, therefore, can be confined in a material bottle. Typically $U_F \sim 200$ neV, which corresponds to velocities of order 5 m/s, wavelengths of order 500 Å and an effective temperature of order 2 mK.

There are two major advantages in using such a neutron source. First, the kinetic energy of UCN is so small that the potential energy associated with the interaction of the neutron magnetic moment with a magnetic field ($\mu \cdot \mathbf{B}$) can be easily made comparable or even higher than the kinetic energy using an electromagnet that can produce a magnetic field of several Tesla (1.7 T field gives $|\mu \cdot \mathbf{B}| = 100$ neV). Therefore, by passing UCNs through a region with a large magnetic field (> 6 T), it is possible to filter out neutrons with one spin state, thereby making them 100% spin-polarized. Second, by operating the accelerator in a pulsed mode, it is possible to limit the emission of background radiation to the period in which the beam pulse strikes the target. By performing a measurement only when there is no beam pulse striking the target, it is possible to perform a measurement with very low background. This is a big advantage of spallation sources over reactor sources, which generate continuous background radiation.

UCNs are produced by the LANSCE solid deuterium UCN source, sent through a polarizer/spin flipper, and then introduced into a decay volume. The wall of the decay volume is a 3 m-long diamond coated quartz cylinder 10 cm in diameter. The decay volume is in the warm bore of a superconducting solenoidal magnet, which provides a holding field of 1 T. The decay electrons spiral along the magnetic field lines towards one of the detectors, and then enter the field expansion region, where the magnetic field is reduced to 0.6 T. As an electron enters the field expansion region, the energy associated with the angular motion of the electron is transferred to longitudinal motion in order to conserve angular momentum as the diameter of the spiral increases due to the reduced field. This reduces the incident angle of the electron onto the detector surface (reverse of the magnetic mirror effect) and suppresses backscattering. The detectors are placed in a region where the expanded field is uniform. The schematic of the UCNA experiment is shown in Fig. 2.

Each electron detector is comprised of a thin low-pressure multiwire proportional chamber (MWPC) placed in front of a plastic scintillator. The MWPC consists of a thin front window (Kelvar supported 6 μm -thick Mylar), a gas volume filled with neopentane, cathode planes made of 50 μm diameter aluminum wires strung with a 2.54 mm spacing, an anode plane made of 10 μm diameter tungsten wires strung with a 2.54 mm spacing, and a thin exit window (6 μm -thick Mylar) [19]. The MWPC provides the position information with a resolu-

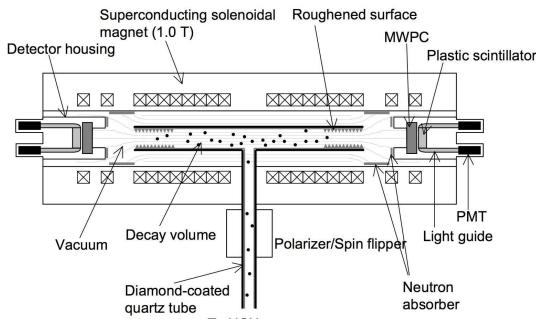


FIG. 2: Schematic of the UCNA Experiment.

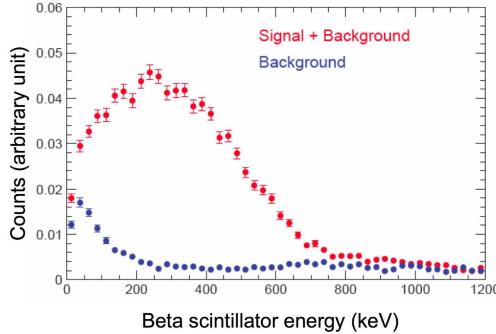


FIG. 3: Spectrum of energy deposited in the plastic scintillation counter

tion of ~ 2 mm, which is important in rejecting β -decay events that occur near the wall of the decay volume. Also the combination of the thin entrance window and the fact that MWPCs are in general more sensitive to small energy depositions than plastic scintillator reduces the fraction of missed backscattered events. On top of this, detailed studies of low energy electron backscattering were performed [20] to help build a reliable model of missed backscattered events, which will be necessary in applying a small correction due to the missed backscattered events to the final results. Furthermore, a small spectrometer was built to provide a monoenergetic electron beam for off-line calibration of the detector system [21].

Figure 3 shows an energy spectrum of the decay electrons from UCNs that the collaboration obtained during their 2006 commissioning run. This is the first β decay spectrum measured with UCNs. The collaboration is hoping to make a 1 – 2% measurement of A during

year 2007.

SUMMARY AND OUTLOOK

Determination of $|V_{ud}|$ from neutron β decay with an improved precision will provide a useful cross check of the current determination of $|V_{ud}|$ from nuclear β decays. Furthermore, precision measurements of neutron decay parameters hold the most promise for a further improvement of the determination of $|V_{ud}|$. Currently there are a number of experiments ongoing and planned that will determine A and a to a relative precision of the order of 0.1%, which, combined with a neutron life measurement with a precision of 0.1%, provide a determination of $|V_{ud}|$ with a similar precision to that from nuclear β decay.

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